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An integrated assessment of the potential of agricultural and forestry residues for energy production in China

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Abstract

Biomass has been widely recognized as an important energy source with high potential to reduce greenhouse gas emissions while minimizing environmental pollution. In this study, we employ the Global Change Assessment Model to estimate the potential of agricultural and forestry residue biomass for energy production in China. Potential availability of residue biomass as an energy source was analyzed for the 21st century under different climate policy scenarios. Currently, the amount of total annual residue biomass, averaged over 2003–2007, is around 15 519 PJ in China, consisting of 10 818 PJ from agriculture residues (70%) and 4701 PJ forestry residues (30%). We estimate that 12 693 PJ of the total biomass is available for energy production, with 66% derived from agricultural residue and 34% from forestry residue. Most of the available residue is from south central China (3347 PJ), east China (2862 PJ) and south-west China (2229 PJ), which combined exceeds 66% of the total national biomass. Under the reference scenario without carbon tax, the potential availability of residue biomass for energy production is projected to be 3380 PJ by 2050 and 4108 PJ by 2095, respectively. When carbon tax is imposed, biomass availability increases substantially. For the CCS 450 ppm scenario, availability of biomass increases to 9002 PJ (2050) and 11 524 PJ (2095), respectively. For the 450 ppm scenario without CCS, 9183 (2050) and 11 150 PJ (2095) residue biomass, respectively, is projected to be available. Moreover, the implementation of CCS will have a little impact on the supply of residue biomass after 2035. Our results suggest that residue biomass has the potential to be an important component in China's sustainable energy production portfolio. As a low carbon emission energy source, climate change policies that involve carbon tariff and CCS technology promote the use of residue biomass for energy production in a low carbon-constrained world.

Keywords: bioenergy, carbon tax, carbon capture and storage, climate policy, integrated assessment, residue biomass

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Introduction

China's energy consumption has been soaring due to rapid increase in population and economic growth over the last decade. Its total energy consumption has increased from 44 022 PJ in 2001 to 110 055 PJ in 2013. Since 2011, China has been the largest energy consumer with oil and natural gas dependency rates of approximately 60% and 33%, respectively (Shi, 2013). The International Energy Agency (IEA) estimates that with an 80% oil dependency rate, China will overtake the United States to become the world's largest oil-demanding country by 2035 (IEA, 2010). Meanwhile, China has overtaken the United States as the world's largest carbon emitter since 2007 and is projected to account for half of the increase in global CO_2 emissions through 2035 (IEA, 2011). In December 2009, China's State Council announced that China will reduce its carbon intensity per unit of GDP by 40–45% by 2020, compared with 2005. Energy security, environmental health and greenhouse

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gases (GHGs) mitigation have been a major impediment to China's sustainable development. Bioenergy is often regarded as an environmentally acceptable and more efficient alternative for energy production (IEA, 2007). China's abundance in biomass resources accentuates the potential of using biomass to promote its development in renewable energy in a carbon-constrained world.

Unlike fossil fuel, biomass energy generates low or even net-zero carbon emissions because CO_2 is recycled during the life cycle of using biomass for energy production. Therefore, temporary and permanent carbon storage based on biogenic sources is thought of as a key way to achieve low CO_2 concentrations and mitigate climate change (Guest *et al.*, 2013). Bioenergy with carbon capture and storage (Bio-CCS) can lead to negative carbon emissions (IEA, 2011). It could potentially have a 33% share of overall mitigation by the end of the century (Klein *et al.*, 2011) and is important to mitigating global warming.

Although large-scale production may incur negative impacts such as increasing food price, accelerating soil erosion and runoff, decreased farmland productivity, and loss of wildlife habitat and biodiversity (Pimentel, 1994; Cramer, 2007), biomass can be environmentally friendly and renewable when used in a sustainable and responsible manner (Gustavsson *et al.*, 2007). Most of the studies on biomass energy were focused on energy production potential, energy conversion technologies, and associated environmental, political and financial problems (Liao *et al.*, 2004; Elmore *et al.*, 2008; Sun *et al.*, 2011; Cui & Wu, 2012; Li *et al.*, 2012; Yu *et al.*, 2012; He *et al.*, 2013). However, previous studies have not examined the potential of biomass as a sustainable energy source in China with a global Integrated Assessment Modeling Framework.

In this study, we estimated the energy potential of agricultural and forestry residue biomass and quantity of residue retention, as well as their spatial distribution in China. We employed the Global Change Assessment Model (GCAM) to simulate the future potential of residue biomass from agricultural and forestry residues for energy production in China in response to global and national energy demand and climate change policies. Results obtained here would improve the understanding of how the development of residue biomass for energy production can help China achieve climate change mitigation goals and contribute to global mitigation efforts.

Materials and methods

Current availability of residue biomass

Determining potential availability of agricultural residues. The four main categories of residue biomass for energy production are agriculture, forestry, municipal solid wastes (MSW) and emerging energy crops. Agricultural residues refer to field (e.g., straw, stalks, stubble, leaves and seed pods) and processed (e.g., husks, seeds, bagasse, molasses and roots) residues from a variety of crops. Agricultural residues are used as fertilizer, forage, raw material for producing paper and generating energy for cooking and heating.

The total amount of agricultural residues was calculated using the estimated ratios of agricultural biomass residue to agricultural product in China (Bi *et al.*, 2008; Bi 2010; Table 1). Not all residue biomass was available due to residue retention and loss during transportation and storage, and subsequent processing. These factors were taken into consideration when estimating the maximum available supply of residue biomass. We used the collectable and usable coefficient (Table 1) of agricultural residues (the ratio of collectable and usable residues to the aboveground biomass of crop) to estimate the maximum available supply of biomass residue (Bi *et al.*, 2008). We also calculated the total potential energy supply by agricultural residues based on their heating values on a dry mass basis. For each crop, we also estimated a residue retention fraction (Table 1) as the amount of residue to be retained for erosion control and nutrient cycling. The yields of main agricultural products of different crops averaged over 2003–2007 are presented in Table 1 and used as the baseline crop yields data for GCAM, for which simulation starts from year 2005 through the end of the 21st century.

Determining the potential availability of forest residues. Forestry residues refer to wastes associated with the processing of forest products including logging residues, wood-processing residues and tending/thinning residues (Cai *et al.*, 2012). Logging residues originate from the harvesting operations and include stumps, roots, leaves, off-cuts, branches and sawdust. These residues are left on forestland. Wood-processing residues, or primary mill residues, are generated when processing roundwood at a sawmill, veneer mill, plywood mill or pulp mill. These residues include discarded logs, bark, sawdust and shavings (Liao *et al.*, 2004; Yuan, 2002). Tending/thinning residues are derived from the processing of tending and thinning of different forests and afforestation activities such as stumping, thinning and pruning. Forest residues are used for generating heat, electricity, liquid fuels and solid fuels (Tan *et al.*, 2010; MOA, 1998).

The total biomass production from logging and tending/thinning residues varies with forest type, location, and tree density and growth rate. The amount of forest residues was estimated by multiplying biomass yields by collectable coefficients of biomass (Table 2). Forests were divided into five categories according to the Forest Law of the People's Republic of China: timber stands, protection forest, economic forest, forest for special uses and firewood forest. In addition, residues from other kinds of forest were evaluated based on the number of trees, their productivity and collectability. In this category, we included sparse forest, shrubs, sipang forest and bamboo forest. Notably, orchards, urban greening forest and hedgerow may produce large amounts of biomass due to annual pruning, which might be a potential bioenergy source. Firewood was assumed to be entirely harvested and currently used for

Table 1 The theoretical maximum energy potential and energy potential availability of agricultural residues in 2003 and 2007

	Type of residue	Residue to product ratio (RPR)	Average Crop production (10^4 t) over (2003–2007)*	Sown area (10^3 ha)†	Water content (%)	Low heating value (KJ kg^{-1})	Collectable coefficient	Retention (t ha^{-1})	Maximum energy potential (PJ)	Energy potential availability (PJ)	Source
Rice	Straws	0.94	17761.68	28318.10	6.00[1]	14059.00	0.83	1.01	2354.78	1954.47	[1] Niu & Liu (1984)
–	Husks	0.21	17761.68	28318.10	9.00[1]	13067.00	0.95	0.00	487.39	463.02	
Wheat	Straws and stalks	1.30	9872.99	22749.90	13.50	14766.00	0.65	1.97	1895.20	1231.88	
Corn	Stalks	1.10	13787.72	26762.52	15.00	14356.00	0.90	0.57	2177.30	1959.57	
–	Cobs	0.21	13787.72	26762.52	9.70	14359.00	0.90	0.00	415.75	374.18	
Other grains	Straws and stalks	1.27	996.31	3917.91	11.35	14384.00	0.86	0.44	181.32	156.39	
Millet	Straws	1.40	173.67	897.19	13.50	14569.00	0.85	0.41	35.42	30.11	
Sorghum	Stalks	1.60	236.75	618.52	10.20	15105.00	0.90	0.61	57.22	51.50	
Barley	Straws and stalks	1.09	316.60	826.68	10.40[2]	13720.00	0.85	0.63	47.35	40.25	[2] Lv & Wang (1998)
Others	Straws and stalks	1.09	269.29	1575.52	11.30	14142.00	0.85	0.28	41.51	35.28	
Beans	Straws stalk leaves pod	1.60	2048.21	12505.55	5.10	14788.50	0.56	1.15	484.64	271.40	
Gram	Straws stalk pod	1.60	90.46	735.45	10.30	14615.00	0.56	0.87	21.15	11.85	
Small red bean	Straws stalk pod	1.60	32.98	219.59	10.30	14548.00	0.56	1.06	7.68	4.30	
Soy beans	Straws stalk leaves pod	1.60	1538.99	9310.13	10.30	15079.00	0.56	1.16	371.30	207.93	
Others	Straws stalk pod	1.60	385.79	2240.38	10.30	14912.00	0.56	1.21	92.05	51.55	
Tubers	Stem and leaves	0.77	3209.70	8924.16	11.80	14125.50	0.73	0.75	349.11	254.85	
Potato	Stem and leaves	0.96	1361.79	4528.09	11.30	13498.00	0.73	0.78	176.46	128.82	
Sweet potato	Stem and leaves	0.63	1847.91	4396.07	12.30	14753.00	0.73	0.72	171.75	125.38	
Cotton	Stalk and torus	5.00[3]	641.08	5521.40	15.00	14979.00	0.86	0.81	480.13	412.91	[3] Cui *et al.* (2008)
Oils crop	–	2.32	2832.62	14775.12	9.92	14775.12	0.78	0.98	971.04	757.41	
Peanut	Stalks	1.50	1360.35	4472.96	10.23[4]	15033.00	0.83	0.78	306.75	254.60	[4] Nan *et al.* (2008)
–	Peanut hull	0.28	1360.35	4472.96	7.80	15682.00	0.70	0.00	59.73	41.81	
Rapes	Stem, leaves, pod	2.87[5]	1183.85	6679.35	10.78[4]	14142.00	0.64	1.83	480.50	307.52	[5] Xie *et al.* (2011)
Sesame	Stem, leaves, pod	2.80	62.82	590.89	10.85[4]	15491.00	0.83	0.51	27.25	22.62	
Sunflower	Residues after Sunflower seed harvest	2.80	156.99	925.69	Air drying	15021.00	0.86	0.66	66.03	56.79	
Flax (linseed)	Hemps blade tips	2.01[5]	37.61	393.60	Air drying	15439.00	0.74	0.50	11.67	8.64	
Others (average)	Stem, leaves, pod	2.00	30.99	1712.63	Air drying	15491.00	0.85	0.05	9.60	8.16	

(continued)

Table 1 (continued)

	Type of residue	Residue to product ratio (RPR)	Average Crop production (10^4 t) over (2003–2007)*	Sown area (10^3 ha)†	Water content (%)	Low heating value (KJ kg^{-1})	Collectable coefficient	Retention (t ha^{-1})	Maximum energy potential (PJ)	Energy potential availability (PJ)	Source
Fiber crops[6]	Sticks, sheath, leaves, hempshell	2.86	93.01	310.10	Air drying	15491.00[7]	0.84	1.37	41.20	34.61	[6] Liu (1986); [7] Jing (2006)
Jute and hemp	Sticks sheath	1.90	9.11	33.62	Air drying	15491.00	0.87	0.67	2.68	2.33	
Flax (Linum)	Sticks sheath	1.10	50.75	123.86	Air drying	15491.00	0.82	0.81	8.65	7.09	
Cannabis sativa	Sticks sheath	3.00	4.69	15.53	Air drying	15491.00	0.86	1.27	2.18	1.87	
Ramie	Leaves hempshell	6.50	27.11	133.97	Air drying	15491.00	0.84	2.10	27.30	22.93	
Others (like jute and hemp)	–	1.90	1.36	3.11	Air drying	15491.00	0.85	1.24	0.40	0.34	
Sugar	Sugar bagasse	0.23	10262.47	1631.71	Air drying	15350	0.97	0.00	355.74	343.31	
–	Sugar cane stalk Sheath	0.10	10262.47	1631.71	Air drying	14902	0.76	1.53	152.93	115.80	
Sugarcane	Bagasse	0.24	9535.30	1421.16	Air drying	15491.00	0.97	0.48	354.51	343.87	
–	Cane stalk sheath	0.10	9535.30		Air drying	13816.00	0.70	–	131.74	92.22	
Sugar beet	Bagasse	0.04	727.17	210.55	13.50	13500.00[8]	0.90	0.14	3.93	3.53	[8] Wang & Liu (1984)
–	Stems leaves	0.10	727.17	210.55	Air drying	14235.00	0.75	–	10.35	7.76	
Tobacco	Stems leaves	1.60	243.95	1249.10	3.51	11300.00[9]	0.95	0.16	44.11	41.90	[9] Zhang *et al.* (2012)
Flue-cured Tobacco	Stems leaves	1.60	220.92	1136.71	3.51	11300.00[9]	0.95	0.16	39.94	37.94	
Others	Stems leaves	1.60	23.03	112.39	Air drying	11300.00[9]	0.95	0.16	4.16	3.96	
Vegetables and Melons	Vine stems shell	0.10	62453.90	19681.70	Air drying	13498.00[11]	0.50	1.59	843.00	421.50	
Total									10817.9	8419.02	

Residue to product ratio, water content, collectable coefficient and low heating value determined following Bi (2010) except [1] to [9].
Residue retention fraction means the minimum to return the field and determined by sown area, collectable coefficient, residue to product ratio (RPR) and crop production.
* and † come from NBS (2003–2007).

Table 2 The theoretical energy potential availability of forestry residues from 2004 to 2008

	Type of residue	Forest area (10^4 ha) (2004–2008)*	Product yield (kg ha^{-1})†	Collectable coefficient‡	Water content	Heating value (KJ kg^{-1})	Retention t ha^{-1}	Energy potential PJ yr^{-1}
Timber stands	Wood chips, sawdust, needle leaves, bark, branches, cone	6007.44	3750	0.50	Dry weight	18600.0	1.31	2095.09
Protection forest	Wood chips, sawdust, bark, branches	8194.68	3750	0.20	Dry weight	18600.0	0.53	1143.16
Forest for special uses	Wood chips, sawdust, bark, branches	1182.14	1875	0.10	Dry weight	18600.0	0.13	41.23
Firewood forest	Total train	174.73	3750	1.00	Dry weight	16747.0	0.00	109.73
Bamboo forest	Wood chips, sawdust, bark, branches	538.10	1875	0.10	Dry weight	17672.1	0.13	17.83
Economic forest	Wood chips, sawdust, bark, branches	2041.00	1875	0.10	Dry weight	18600.0	0.13	71.18
Sparse forest	Wood chips, sawdust, bark, branches	482.22	1875	0.50	Dry weight	18600.0	0.66	84.09
Shrubbery	Bark, branches	5365.34	938	0.50	Dry weight	18600.0	0.33	468.04
Sipang forest	Wood chips, sawdust, bark, branches	1121054.00 (10^4zhu)	2 (kg zhu^{-1})	0.50	Dry weight	18600.0	0.00	208.52
City greening forest; Hedgerow	Wood chips, sawdust, bark, branches	400.00[1]	1625	0.10	Dry weight	18600.0	0.11	12.09
Orchard	Fruitwood, pruning coconut shell, chestnut shell, walnut shell, etc.	996.66[2]	1875	0.10	Dry weight	18600.0	0.13	34.76
Mill	Lath, slab, woodshaving	10675.27	540 (kg m^{-3})	0.34	Dry weight	19500.0[3]	0.00	382.20
Waste wood products		2000.00[1]	250 (kg m^{-3})	0.34	Dry weight	19500.0[3]	0.00	33.15
Total								4701.06

*Comes from SFA (2009) except [1] Cai *et al.*, 2012 and [2] NBS (2004–2008), † and ‡ determined following MOA, 1998 and Lu, 1997; Heating value derives from MOA, 1998 except [3] Zhang *et al.*, 2008. Residue retention fraction determined by forest area, collectable coefficient, product yield based on assumption of the 30% availability of forest residues (MOA, 1998).

heating in rural areas. For wood-processing residues, the available amount was estimated based on the average annual production of roundwood in 2005 and 2009, which included net imported roundwood. These residues collectively accounted for ca. 34.4% of the total roundwood production (MOA, 1998). For forest residues, we also estimated (i) the maximum available supply of residue biomass based on the coefficients of collectable residues, (ii) the total potential energy supply from forestry residues according to their heating values (Table 2) and (iii) a residue retention value (Table 2).

While agricultural residues and forestry residues were the major focus of our study, MSW and energy crops were also considered and discussed. Note that the information provided here only reflects the gross amount of residues and energy potentials, which were derived based on the assumption that all the residues were economically exploitable and fully utilized.

The potential of residue biomass in the future

To better describe the interrelations between agriculture, food, bioenergy and climate change and understand the potential role of this energy resource in the future, the residue availability parameters particularly derived for China, as introduced in the above section, were incorporated into the Global Change Assessment Model (GCAM) to simulate future availability of residue biomass for bioenergy production in response to global mitigation policies.

The GCAM is a long-term partial equilibrium model with 32 energy/economy regions and 283 agro-ecological zones (AEZs). Besides, it also includes a reduced form carbon cycle and climate module and runs from 1990 to 2100 in 5-year time step. GCAM was designed to estimate the long-term changes in the global energy/economy, agriculture/land use and water use and further explore the interactions between sectors (Kim *et al.*, 2006). It will serve for understanding the potential ramifications of climate mitigation actions. GCAM has been used to investigate the potential roles of specific policy measures and different energy technologies such as bioenergy, CCS (carbon capture and storage), nuclear energy and other technologies used in different sectors Clarke *et al.*, 2007a; (Thomson *et al.*, 2011). We used the standard release of GCAM 3.0 with a thorough representation of bioenergy, agriculture and land

use as described in (Wise *et al.*, 2009; Wise & Calvin 2011; Wise *et al.*, 2014). GCAM can model three types of commercial biomass energy including dedicated energy crops, municipal solid waste and residue biomass (Wise *et al.*, 2009; Luckow *et al.*, 2010; Kyle *et al.*, 2011). Biomass energy production from dedicated crops is mainly dependent on the availability and characteristics of land resources, technology options for production, competing land uses as well as bioenergy price in the context of energy markets. Potential energy production from residue biomass depends on crop production, harvest index and price of bioenergy. Potential production is also influenced by population and income. Carbon fluxes associated with terrestrial ecosystems were simulated in 15 different carbon pools (Wise *et al.*, 2009), which inform bioenergy production under a carbon-constrained world.

For this analysis, the GCAM was used to simulate future bioenergy production from residue biomass under a reference scenario and two policy scenarios with and without CCS that are targeted at 450 ppm atmospheric concentration of CO_2 by the end of the 21st century. The reference scenarios (Business as Usual) do not have greenhouse gas emissions constraints or taxes. For the policy scenario with carbon tax, we assumed that carbon emissions from the terrestrial ecosystems, fossil fuel and industrial sources are equally charged with a carbon price starting in 2020 and increasing at 5% per year through 2100. This scenario is noted as UCT (Universal Carbon Tax) (Edmonds *et al.*, 2008; Wise *et al.*, 2009). The carbon price pathway was set to limit atmospheric CO_2 concentration to 450 ppm. In the other policy scenario, bioenergy with CCS detailed in Clarke *et al.* (2007b) was also considered, which has been shown as an effective technology to greatly reduce CO_2 emissions for achieving low CO_2 concentration targets. The policy scenario without CCS would be of higher cost. We used different carbon price starting in 2020 at approximately 76 $\$ t^{-1} C^{-1}$ (in 2005$) without CCS and 129 $\$ t^{-1} C^{-1}$ (in 2005$) with CCS. Future crop productivity needs be considered for projecting the energy production from residue biomass in the future. In the reference scenario, change in crop yield was based on FAO projection until 2050 to ensure global food security (Briunsma, 2009). Consistent with the historical trend, we assumed yields increase at a slower growth rate in the developed countries, but a relatively high yield growth rate in the developing countries. For instance, in China, the crop yield increase rates are 0.83%,0.62% and 0.35% for 2020, 2035 and 2050, respectively (Kyle *et al.*, 2011). After 2050, the annual agriculture productivity changes converge to 0.25% for all crops and regions in the world. Global population growth pathway was inherited from United Nation's 2011 (Eom *et al.*, 2012). Chinese population and GDP growth was described in Jiang *et al.* (2009), peaking in around 2035 and decreasing thereafter due to population aging and low birth rate. We assumed that GDP increases at a fast growth rate in China before 2030, and changes to a lower growth rate close to other developed countries beyond that (Jiang *et al.*, 2009; Zhou *et al.*, 2013). In this study, we used the same social and macroeconomic drivers, including population, labor productivity and changes in crop productivity, for all the scenarios.

Results

Current availability of agricultural residues

The total amount of agricultural residues and available energy supply are about 10 818 PJ and 8419 PJ per year, respectively (Table 1). This energy supply is roughly 8% of the annual energy consumption (105 952 PJ) of China in 2012. The energy potential of rice residues (including rice husks) is the greatest (around 2418 PJ), followed by corn residues (including corn cobs) of 2334 PJ and wheat straws (1232 PJ). These three crop residues combined account for ca. 71% of the total potentially available energy supply. The total processing crop residues, including rice husks, corn cobs, sugar bagasse and peanut hull, account for approximately 1319 PJ and 1223 PJ, respectively, which dominantly represent about 12% and 15% of the total residue availability.

The potential availability of crop residues for energy production in China was also analyzed spatially in Table 3. South central China has the highest potential for crop residue-based energy production of ca. 2419 PJ, followed by east China with ca. 2198 PJ. North-east China has the lowest potential of ca. 648 PJ. Other districts, including south-west China, north-west China and north China, combined have the potential to provide crop residue-based energy production of more than 3156 PJ. In China, Henan, Shandong, Jiangsu, Guangxi, Sichuan, Hubei and Heilongjiang are the top seven provinces in terms of potential availability of agricultural residues, occupying 46.5% of the total availability. Rice residues are mainly available over the central south China, east China and south-west China, accounting for 86.7% (2098 PJ) of the national rice residue potential. Wheat residue is mainly available in north China, east China and south central China, which collectively account for about 80.5% of the total of 1232 PJ. Henan, Shandong and Anhui provinces in located in these three districts account for about 70.1% of the total wheat residue availability. The energy production potential of corn residues is distributed mainly over north-west China and north China, amounting to 51.4% of the total national availability. The availability of the two root crops, viz. sugarcane and sugar beet, is the highest in Guangxi, Yunnan and Guangdong of central south and south-west of China, accounting for 82.9% of the national energy production potential of 459 PJ (Table 3).

Current availability of forest residues

The total amount of forest residues for energy production was estimated at ca. 4274 PJ per year (Table 4) based on the data of the seventh National Forestry

Table 3 The spatial distribution of the theoretical energy potential available of agricultural residues in 2003 and 2007 at province level (PJ)

	Rice	Rice husks	Wheat	Corn	Corn cobs	Other grains	Beans	Tubers	Cotton	Oils crop	Peanut hull	Sugar bagasse	Sugar cane stalk sheath	Fiber crops	Tobacco	Vegetables and Melons	Total
Residue to product ratio (RPR)	0.94	0.21	1.3	1.1	0.21	1.27	1.6	0.77	5	2.32	0.28	0.23	0.1	2.86	1.6	0.1	
Heating value (KJ kg^{-1}) low	14 059	13 067	14 766	14 356	14 359	14 384	14788.5	14125.5	14 979	14775.1	15 682	15349.9	14 902	15 491	11 300	13 498	
Collectable coefficient	0.83	0.95	0.65	0.9	0.9	0.86	0.56	0.73	0.86	0.78	0.7	0.96504	0.7572	0.84	0.95	0.5	
Beijing	0.06	0.01	2.89	8.18	1.56	0.08	0.34	0.20	0.23	0.70	0.08	0.00	0.00	0.00	0.00	3.13	15.82
Tianjin	1.08	0.26	5.53	10.54	2.01	0.20	0.46	0.05	6.27	0.37	0.02	0.00	0.00	0.00	0.00	3.35	28.11
Hebei	5.47	1.30	139.89	176.11	33.63	8.96	6.87	7.86	41.08	39.68	4.17	1.31	0.44	0.22	0.14	45.45	474.78
Shanxi	0.10	0.02	28.51	86.16	16.45	9.97	5.66	5.11	7.20	6.09	0.09	0.35	0.12	0.01	0.12	6.53	155.97
Inner Mongolia	6.02	1.43	16.99	147.47	28.16	13.61	19.03	13.54	0.26	27.20	0.07	3.73	1.26	0.65	0.31	8.00	259.53
North China	**12.74**	**3.02**	**193.81**	**428.47**	**81.82**	**32.82**	**32.37**	**26.77**	**55.04**	**74.04**	**4.43**	**5.39**	**1.82**	**0.88**	**0.56**	**66.47**	**934.20**
Liaoning	46.24	10.95	0.78	156.39	29.86	14.59	6.53	4.01	0.19	10.49	1.10	0.14	0.05	0.01	0.49	15.08	265.95
Jilin	48.78	11.56	0.35	257.62	49.19	8.92	18.76	3.91	0.07	12.13	0.79	0.18	0.06	0.11	0.79	6.45	369.67
Heilongjiang	129.23	30.62	9.45	164.08	31.33	10.02	82.72	7.13	0.00	11.10	0.14	4.26	1.44	11.25	1.01	9.66	471.96
North-east China	**224.25**	**53.13**	**10.57**	**578.08**	**110.38**	**33.52**	**108.02**	**15.05**	**0.27**	**33.72**	**2.03**	**4.58**	**1.54**	**11.36**	**2.29**	**31.19**	**1107.58**
Shanghai	9.53	2.26	1.28	0.39	0.07	0.52	0.35	0.06	0.12	1.59	0.01	0.34	0.12	0.00	0.00	3.38	19.92
Jiangsu	183.18	43.40	97.33	27.94	5.33	13.69	11.56	4.55	23.43	52.16	1.57	0.67	0.23	0.17	0.01	26.35	484.67
Zhejiang	72.58	17.19	2.39	2.54	0.48	1.91	4.93	3.36	1.48	11.30	0.13	2.90	0.98	0.05	0.07	14.25	135.93
Anhui	136.36	32.30	109.58	38.77	7.40	7.55	15.68	8.51	21.97	64.78	2.31	0.81	0.27	1.29	0.44	15.11	453.40
Fujian	57.12	13.53	0.24	1.72	0.33	0.32	2.78	10.35	0.02	6.86	0.74	2.86	0.96	0.01	2.00	9.94	108.72
Jiangxi	180.95	42.87	0.31	0.85	0.16	0.18	3.40	4.32	6.31	20.94	1.08	2.56	0.86	0.45	0.42	8.63	273.06
Shandong	10.55	2.50	223.56	233.41	44.57	2.40	8.35	17.00	62.41	93.70	10.64	0.00	0.00	0.13	1.47	66.39	721.86
East China	**650.28**	**154.05**	**434.70**	**305.61**	**58.36**	**26.57**	**47.06**	**48.13**	**115.74**	**251.31**	**16.48**	**10.14**	**3.42**	**2.10**	**4.40**	**144.06**	**2197.57**
Henan	39.60	9.38	331.09	177.33	33.86	6.22	11.49	13.22	42.26	112.95	9.83	0.67	0.23	1.46	4.23	45.58	795.71
Hubei	160.70	38.07	30.32	27.02	5.16	2.63	7.69	10.19	28.40	74.34	1.78	1.31	0.44	1.96	1.48	21.57	406.12
Hunan	252.91	59.92	1.26	17.22	3.29	1.37	6.22	10.82	13.33	33.47	0.79	3.26	1.10	5.22	3.17	18.07	427.33
Guangdong	120.44	28.53	0.14	8.06	1.54	0.72	2.84	13.51	0.00	20.95	2.37	37.83	12.76	0.06	0.93	17.60	264.36
Guangxi	126.72	30.02	0.17	27.02	5.16	0.30	4.28	4.59	0.08	13.08	1.34	194.92	65.75	0.42	0.46	14.47	482.28
Hainan	14.78	3.50	0.00	0.83	0.16	0.09	0.24	2.76	0.00	2.15	0.24	11.86	4.00	0.04	0.00	2.57	42.84
Central south China	**715.15**	**169.42**	**362.98**	**257.47**	**49.16**	**11.32**	**32.76**	**55.10**	**84.08**	**256.95**	**16.35**	**249.85**	**84.27**	**9.15**	**10.27**	**119.86**	**2418.64**
Chongqing	52.04	12.33	8.72	31.34	5.98	1.36	4.69	20.00	0.01	9.75	0.24	0.37	0.13	0.44	1.46	5.90	148.54

(continued)

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Table 3 (continued)

	Rice	Rice husks	Wheat	Corn	Corn cobs	Other grains	Beans	Tubers	Cotton	Oils crop	Peanut hull	Sugar bagasse	Sugar cane stalk sheath	Fiber crops	Tobacco	Vegetables and Melons	Total
Sichuan	159.64	37.82	54.02	79.91	15.26	9.57	15.16	34.83	1.49	57.91	1.70	4.36	1.47	2.34	2.85	18.79	480.17
Guizhou	50.25	11.90	7.92	48.09	9.18	1.70	4.97	16.05	0.04	20.20	0.20	2.28	0.77	0.06	5.74	5.69	175.66
Yunnan	68.76	16.29	13.40	64.00	12.22	7.59	10.55	13.69	0.01	7.81	0.14	51.93	17.52	3.02	12.79	6.78	294.13
Tibet	0.06	0.01	3.29	0.24	0.04	9.70	0.42	0.09	0.00	1.45	0.00	0.00	0.00	0.00	0.00	0.26	15.52
South-west China	**330.74**	**78.35**	**87.35**	**223.58**	**42.69**	**29.93**	**35.80**	**84.65**	**1.55**	**97.13**	**2.27**	**58.95**	**19.88**	**5.86**	**22.83**	**37.42**	**1114.03**
Shaanxi	8.71	2.06	48.82	62.25	11.89	2.54	4.99	5.56	5.04	11.40	0.22	0.08	0.03	0.04	0.97	6.59	159.08
Gansu	0.42	0.10	32.63	34.09	6.51	13.85	5.12	14.38	7.27	12.42	0.01	0.65	0.22	0.46	0.51	6.39	128.50
Qinghai	0.00	0.00	5.84	0.14	0.03	2.03	1.42	1.87	0.00	7.45	0.00	0.01	0.00	0.01	0.01	0.59	19.36
Ningxia	6.33	1.50	9.49	17.98	3.43	1.14	0.72	2.26	0.01	2.96	0.00	0.01	0.00	0.00	0.02	1.79	44.21
Xinjiang	5.85	1.38	45.68	51.90	9.91	3.27	3.14	1.07	143.97	9.97	0.02	13.66	4.61	4.75	0.03	7.14	296.42
North-west China	**21.31**	**5.05**	**142.46**	**166.36**	**31.77**	**22.82**	**15.40**	**25.14**	**156.27**	**44.20**	**0.25**	**14.41**	**4.86**	**5.26**	**1.54**	**22.50**	**647.58**
Total	1954.47	463.02	1231.88	1959.57	0.00	156.98	271.40	254.85	412.95	757.36	0.00	343.31	115.80	34.61	41.90	421.50	8419.59

Survey (2004–2008), when forest area reached 195×10^6 ha and covered 20.4% of China's land. The energy potential of timber stands is the greatest (around 2095 PJ), followed by protection forest of 1143 PJ. These four main forestry residues combined account for ca. 73.6% of the total potentially available energy supply. The total amount of residues from other forest types is about 778.48 PJ accounting for ca. 16.6% of the total potentially available energy supply. The total wood-processing residues account for approximately 415 PJ, which represents about 8.9% of the total residue availability. The residues of orchards, urban greening forest and hedgerow are of the lowest potential of ca. 46.9 PJ accounting 0.99% of the total forestry residues. The energy potential of logging (including tending/thinning residues) and mills residues was about 4286 PJ and 415 PJ, respectively, with north-east China, north China and south-west China having the largest amount of forest residues availability. The top five provinces in terms of forest residue availability are Yunnan, Heilongjiang, Inner Mongolia, Sichuan and Guangxi, which combined account for 41.4% of total logging residue.

Combined agricultural and forest residue availability

The total energy potential from all sources is about 12 693 PJ per year (Table 5), with agricultural residues contributing about 8419 PJ each year. The total energy potential of forest residues is ca. 4274 PJ each year (excluding city greening forest; hedgerow, mills and waste wood). Agricultural residues alone contribute more than 66% of the national energy potential of biomass residues. The spatial distribution of the potential availability of biomass residues for energy production is shown in Tables 5 and 6. The total residue availability was the highest in south central China (3347 PJ), followed by the east China and south-west China with 2862 and 2229 PJ, respectively. These three regions collectively account for over 66% of the national residue availability.

Future residue biomass availability under different scenarios

The total bioenergy potential from agricultural residues, forest residues and mills will reach 17 660, 21 710 and 21 980 PJ by 2050 under BAU, CCS450 and NOCCS450, respectively, and 17 320, 21 180 and 21 640 PJ by the end of the 21st century, as a result of an increase in food demand, agriculture productivity and crop price. The energy potential under the reference scenario is lower than that of the two policy scenarios (Table 6).

To project bioenergy production in the future, bioenergy price was calculated within the GCAM based on energy demand and competition with other energy

Table 4 The spatial distribution of the theoretical energy potential availability of forestry residues from 2004 to 2008 (PJ)

	Timber stands	Protection forest	Forest for special uses	Firewood forest	Bamboo forest	Economic forest	Sparse forest	Shrubbery	Sipang forest	Orchard	Total
Product yields (kg ha^{-1})	3750	3750	1875	3750	1875	1875	1875	938	2	1875	
Collectable coefficient	0.5	0.2	0.1	1.0	0.1	0.1	0.5	0.5	0.5	0.1	
Heating value KJ kg^{-1}	18 600	18 600	18 600	16 747	17672.1	18 600	18 600	18 600	18 600	18 600	
Beijing	0.88	4.13	0.12	0.08	0.00	0.57	0.04	3.32	0.36	0.27	9.76
Tianjin	0.24	0.61	0.02	0.00	0.00	0.13	0.03	0.17	0.24	0.13	1.55
Hebei	23.03	28.37	0.36	5.36	0.00	3.18	1.46	8.97	70.70	3.82	145.24
Shanxi	8.10	19.07	0.42	0.19	0.00	1.58	3.14	10.36	3.34	0.96	47.18
Inner Mongolia	148.02	154.20	5.28	0.00	0.00	0.69	11.84	61.32	1.61	0.17	383.14
North China	**180.27**	**206.38**	**6.20**	**5.63**	**0.00**	**6.16**	**16.50**	**84.14**	**76.24**	**5.36**	**586.87**
Liaoning	44.47	26.23	0.47	20.23	0.00	4.26	0.99	5.12	2.13	1.09	105.00
Jilin	128.10	44.41	1.39	0.81	0.00	0.31	2.15	1.38	0.76	0.25	179.57
Heilongjiang	186.15	169.93	5.52	1.60	0.00	0.50	2.84	0.56	1.95	0.14	369.18
North-east China	**358.72**	**240.57**	**7.38**	**22.64**	**0.00**	**5.08**	**5.98**	**7.07**	**4.83**	**1.49**	**653.75**
Shanghai	0.03	0.12	0.08	0.00	0.01	0.08	0.00	0.03	0.47	0.09	0.91
Jiangsu	18.40	2.38	0.16	0.08	0.12	1.03	0.06	0.10	8.37	0.64	31.35
Zhejiang	79.66	21.88	0.29	0.00	2.59	3.92	0.67	2.74	4.13	1.04	116.92
Anhui	63.40	10.93	0.25	2.18	1.07	1.98	1.23	3.06	7.22	0.36	91.68
Fujian	130.63	21.51	1.17	2.26	3.29	3.53	1.59	1.81	0.73	1.91	168.44
Jiangxi	127.03	50.18	1.21	6.04	2.82	4.20	0.78	1.73	1.95	1.04	196.97
Shandong	29.83	9.33	0.13	0.00	0.00	3.43	1.17	0.74	10.56	2.56	57.75
East China	**448.98**	**116.34**	**3.29**	**10.55**	**9.91**	**18.17**	**5.51**	**10.20**	**33.44**	**7.64**	**664.04**
Henan	43.97	19.22	0.60	1.51	0.07	1.78	1.12	5.36	20.88	1.43	95.94
Hubei	42.63	49.50	0.50	10.25	0.50	1.94	2.18	12.56	4.90	0.94	125.89
Hunan	152.33	36.58	0.87	1.61	2.08	5.52	2.40	12.38	3.36	1.50	218.63
Guangdong	152.75	25.97	1.79	2.11	1.35	4.55	2.43	5.81	0.92	3.44	201.12
Guangxi	195.87	28.35	1.16	5.43	0.99	6.87	2.68	21.50	2.41	2.99	268.24
Hainan	8.28	5.10	0.83	0.00	0.05	3.16	0.04	0.33	0.37	0.58	18.74
Central south China	**595.83**	**164.71**	**5.75**	**20.91**	**5.04**	**23.82**	**10.85**	**57.95**	**32.84**	**10.87**	**928.57**
Chongqing	18.13	16.22	0.46	0.40	0.41	0.67	2.55	8.90	13.76	0.63	62.14
Sichuan	116.68	103.77	2.86	3.05	1.61	3.47	8.73	63.49	22.67	1.61	327.93
Guizhou	37.75	35.07	0.83	9.25	0.44	1.68	3.29	10.92	3.51	0.40	103.14
Yunnan	241.81	81.67	5.52	22.31	0.30	5.81	9.03	32.90	6.16	0.82	406.34
Tibet	49.34	81.59	3.98	0.35	0.00	0.02	5.04	74.55	0.67	0.00	215.56
South-west China	**463.72**	**318.31**	**13.65**	**35.36**	**2.76**	**11.65**	**28.64**	**190.77**	**46.78**	**3.46**	**1115.10**
Shaanxi	45.49	53.18	1.15	14.05	0.12	4.05	5.02	16.04	2.97	2.86	144.94
Gansu	1.32	19.86	2.35	0.00	0.00	0.90	2.99	29.93	5.85	1.25	64.46
Qinghai	0.25	1.74	0.78	0.00	0.00	0.01	1.18	28.43	0.50	0.02	32.90
Ningxia	0.08	0.71	0.20	0.00	0.00	0.16	0.36	3.31	0.65	0.18	5.65
Xinjiang	0.42	21.35	0.49	0.60	0.00	1.20	7.06	40.20	4.41	1.62	77.35
North-west China	**47.57**	**96.85**	**4.96**	**14.65**	**0.12**	**6.31**	**16.61**	**117.91**	**14.38**	**5.93**	**325.30**
Total	2095.09	1143.16	41.23	109.73	17.83	71.18	84.09	468.04	208.52	34.76	4273.62

The theoretical energy potential availability of forestry residues did not include mill and waste products because of no available data at province level.

Table 5 The total theoretical energy potential availability of agriculture and forestry residues (PJ)

	Forestry residues	Agriculture residues	Total
Beijing	9.76	15.82	25.58
Tianjin	1.55	28.11	29.67
Hebei	145.24	474.78	620.02
Shanxi	47.18	155.97	203.15
Inner Mongolia	383.14	259.53	642.66
North China	**586.87**	**934.20**	**1521.07**
Liaoning	105.00	265.95	370.95
Jilin	179.57	369.67	549.24
Heilongjiang	369.18	471.96	841.14
North-east China	**653.75**	**1107.58**	**1761.33**
Shanghai	0.91	19.92	20.83
Jiangsu	31.35	484.67	516.02
Zhejiang	116.92	135.93	252.86
Anhui	91.68	453.40	545.09
Fujian	168.44	108.72	277.17
Jiangxi	196.97	273.06	470.03
Shandong	57.75	721.86	779.61
East China	**664.04**	**2197.57**	**2861.60**
Henan	95.94	795.71	891.65
Hubei	125.89	406.12	532.01
Hunan	218.63	427.33	645.96
Guangdong	201.12	264.36	465.48
Guangxi	268.24	482.28	750.52
Hainan	18.74	42.84	61.58
Central south China	**928.57**	**2418.64**	**3347.21**
Chongqing	62.14	148.54	210.68
Sichuan	327.93	480.17	808.10
Guizhou	103.14	175.66	278.80
Yunnan	406.34	294.13	700.47
Tibet	215.56	15.52	231.08
South-west China	**1115.10**	**1114.03**	**2229.12**
Shaanxi	144.94	159.08	304.02
Gansu	64.46	128.50	192.96
Qinghai	32.90	19.36	52.26
Ningxia	5.65	44.21	49.86
Xinjiang	77.35	296.42	373.78
North-west China	**325.30**	**647.58**	**972.88**
Total	4273.62	8419.59	12693.21

Table 6 The theoretical maximum energy potential under different scenario (EJ)

	2020	2035	2050	2065	2080	2095
BAU	16.70	17.46	17.66	17.77	17.63	17.32
CCS450	18.71	20.65	21.71	22.09	21.87	21.18
NOCCS450	19.16	21.08	21.98	22.45	22.33	21.64

sources. Figure 1 shows the bioenergy prices for BAU and two limitation concentration scenarios. Growth of bioenergy market prices over time is enhanced by carbon price in a perspective of economics. Note that the

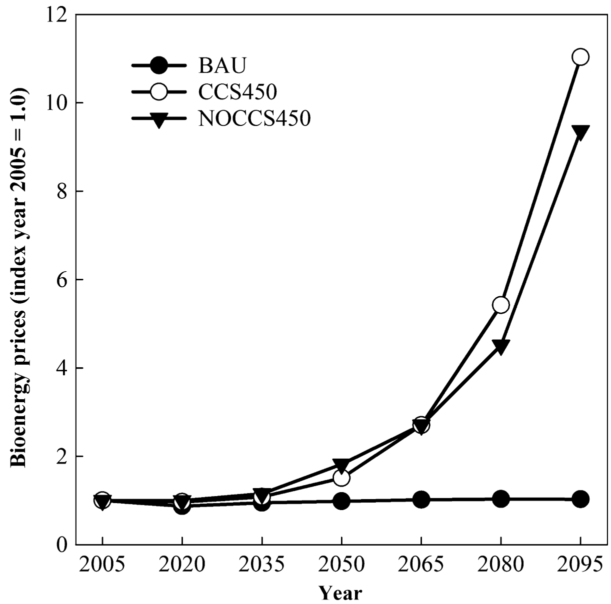

Fig. 1 Bioenergy prices along two alternative UCT CO_2 concentration target pathways (index year 2005 = 1.0). Growth of bioenergy market prices over time is enhanced by carbon price under climate policy scenarios in a perspective of economics.

carbon price was not added to the price of bioenergy based on the assumption of zero carbon emissions from bioenergy production (Wise *et al.*, 2009). Bioenergy price under the policy scenarios is much than that in the reference scenario after 2035. Among the two policy scenarios, bioenergy price under the NOCCS 450 ppm scenario has a competitive advantage compared to the CCS 450 ppm mitigation scenario after 2065, as evidenced by the trends of more bioenergy production from energy crop until the carbon prices are very high.

In the reference scenario without carbon tax, more and more residue biomass from agriculture and forestry becomes available along with increase in energy demand and energy prices and reaches a projected output of approximately 3380 PJ yr^{-1} by 2050 and 4108 PJ yr^{-1} by 2095 (Fig. 2). Under the UCT scenarios, the carbon price is charged for the emission of CO_2. This intensifies the demand and increases price of residue biomass for energy and further decreases the use of fossil fuels. The total bioenergy production from residue biomass is 9000 and 9180 PJ by 2050 under CCS 450 ppm and NOCCS 450 ppm, respectively, and 11 520 and 11 150 PJ by the end of the century, respectively (Fig. 2).

Figure 3 shows the carbon prices calculated within the GCAM that are required to drive a fundamental transformation of the global economy. To achieve the 450 ppm CO_2 concentration targets, the policy scenario without CCS will require higher carbon prices than the policy scenario with CCS, especially toward the end of

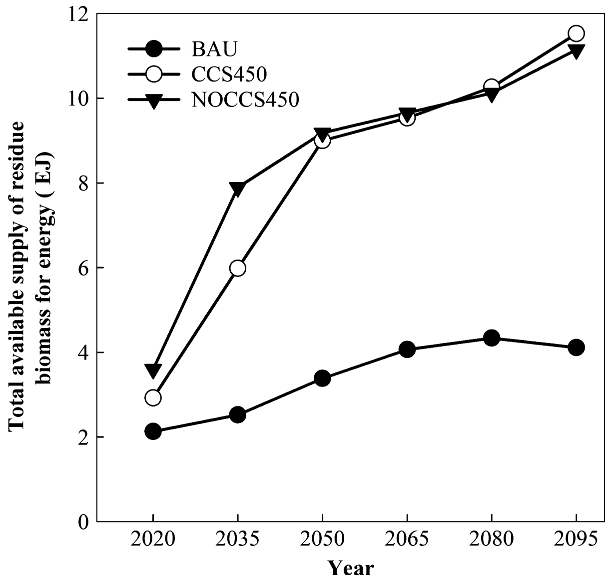

Fig. 2 The total available supply of residue biomass for energy under different scenarios from 2020 to 2095 (EJ). More and more residue biomass from agriculture and forestry becomes available along with increase in energy demand and energy prices, and the carbon price is charged under climate policy scenarios, which further intensifies the demand and increases price of residue biomass for energy.

the century. For example, the 2095 carbon price for the CCS 450 ppm scenario is 5004 \$ t^{-1} C^{-1}, which is much higher than the carbon price of 2955 \$ t^{-1} C^{-1} under NOCCS 450 ppm in 2095. However, the two policy scenarios do not differ substantially from each other in terms of supply of residue biomass after 2035 (Fig. 2).

Figure 4 shows the total bioenergy production (including residue biomass, energy crop and MSW) increases substantially over time under all three climate policy scenarios, but with higher bioenergy production under the CCS 450 ppm CO_2 scenario than that under the other two scenarios after 2050. The NOCCS 450 ppm CO_2 scenario projects more bioenergy production compared with the other two scenarios before 2050.

Figure 5 shows the proportion of bioenergy production from residue biomass over time in the total bioenergy production. In the reference scenario, bioenergy production from energy crops accounts for about 65% of the total bioenergy production after 2035, as a result of no CO_2 emission limitation. In the CCS 450 ppm CO_2 scenario, residue biomass meets nearly half all the bioenergy production in 2035, 53% by mid-century and 40% by the end of the century. In the NOCCS 450 ppm CO_2 scenario, residue biomass contributes ca. 60% of all the total bioenergy production in 2035, 55% by 2050 and

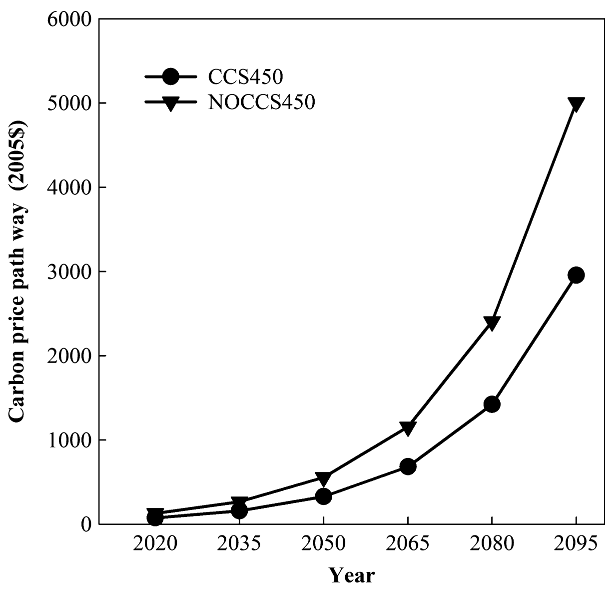

Fig. 3 Carbon price pathway under different climate policy scenario (2005\$). The carbon prices calculated within the GCAM that are required to drive a fundamental transformation of the global economy. The policy scenario without CCS will require higher carbon prices than the policy scenario with CCS, especially toward the end of the century for achieving the 450 ppm CO_2 concentration targets.

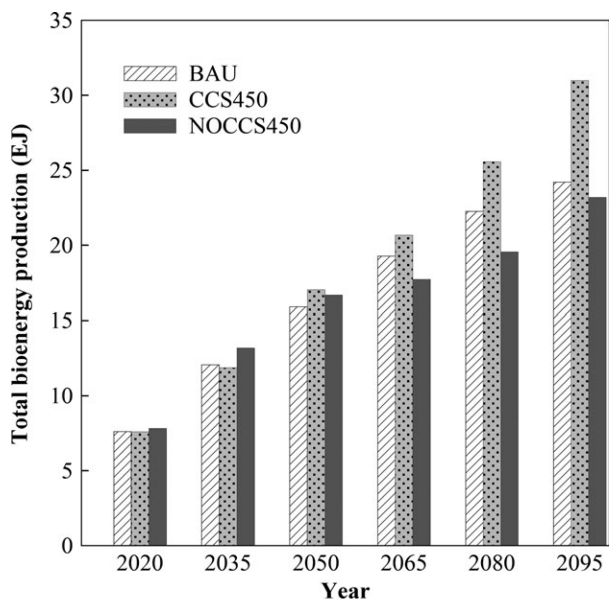

Fig. 4 The total bioenergy production (including residue biomass, energy crop and MSW) under different scenarios (EJ). In the future, the total bioenergy production substantially shows an increases, but with higher bioenergy production with the CCS scenario than that under two other scenarios after 2050, and the NOCCS scenario accounts for a great proportion in bioenergy production compared with two other scenarios before 2050.

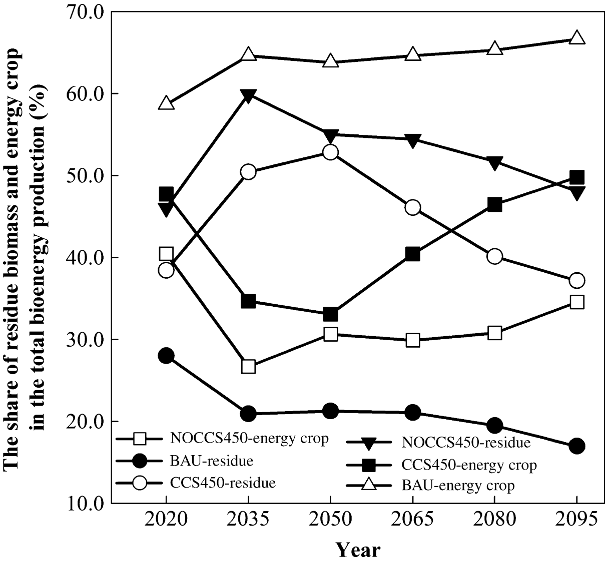

Fig. 5 The share of residue biomass and energy crop in the total bioenergy production under different scenarios. In the CCS scenario, residue biomass meets nearly half all the bioenergy production in 2035, 53% by mid-century and 40% by the end of the century. In the NOCCS scenario, residue biomass accounts for about 60% of all the total bioenergy production in 2035, 55% by 2050 and 48% by the 2095. Bioenergy production from energy crops contributes to about 65% of the total bioenergy production after 2035 in the BAU.

48% by the 2095. Total bioenergy production will contribute about 31% of the total energy production by 2050 and 35% by 2095. These results show that more biomass energy from residue biomass will be produced under climate policies without carbon tax and additional land and that trade-off between energy prices competitiveness, options of low carbon technology (CCS) and climate policy (carbon tax) is required for bioenergy production.

Discussion

We evaluated the energy potential of agricultural and forest residues in China and found that the total potential is about 12 693 PJ per year under current conditions. This is close to 10% of the total primary energy demand of China in 2013 (110 055 PJ). However, it is important to note these estimated values may be affected by the availability and reliability of data on crop species, harvest index, location, soil properties and seasonal variation (Liao *et al.*, 2004; Zhou *et al.*, 2011). The potential of agricultural residues as a bioenergy source is complicated by their numerous alternative uses including feeding, fodder, fertilizer, household fuels and industrial fuels. Currently, agricultural residues are mainly used for forage (24.5%), industry materials (3.9%), base material for edible mushrooms (2.3%), biogas (0.85%), direct field restoration (14.1–14.6%), direct combustion by farmers (24.9–30.7%), whereas the rest are lost during collection (15%), being discarded or directly burnt (12.3–20.5%) in the field (Bi *et al.*, 2008; Wang *et al.*, 2010). At present, the collectable and utilizable amount of agriculture residues as a bioenergy resource is estimated to be around only 23.9%. In addition, the actual availability is also limited by economic, social, environmental, institutional and policy incentives, logistical considerations, infrastructural and technological constraints, and availability of skilled personnel (Bi, 2010; Okello *et al.*, 2013).

Overall, most of residue biomass should be returned to the field for improving soil fertility through maintaining soil organic matter and soil structure. The reasonable residue incorporation rate of 3.0–4.5 t ha^{-1} has been reported to slightly increase soil organic carbon and crop yield for rice and wheat and 4.5–6.0 t ha^{-1} for corn in China. The amount of residue retention was 1 911 721 $\times$ 10^4 t, accounting for 22.7% of the total residue biomass in 2008. If the amount of residues returned directly to fields (92 $\times$ 10^6 t accounting for 10.9% of the total residue biomass in 2008) is also considered, the amount of residue retention represents one-third of the total residue biomass in 2008, when a residue retention ratio of 2.33 t ha^{-1} is used (Bi, 2010). Note that this residue retention ratio is lower than the desired residue retention ratio for maintaining sustainable agroecosystems, which is an important factor in collecting residue biomass for energy production.

Not all forest residues are harvestable. Some of them must be retained for maintaining nutrient levels and preventing soil erosion. This study identified that the logging and processing forest residues would potentially provide 4701 PJ of energy. Significant variation in the potential is observed, as influenced by numerous factors such as forest type, collectable fraction and geographical location. For example, the average yield of firewood forest in the southern mountain area is as high as 7.5 t ha^{-1}, but only 3.75 t ha^{-1} in the North Mountain area. The yield shrub forest is 0.75 t ha^{-1} over the country, with a collectable coefficient of 0.2 in the mountain area and 0.5 in the plains area (Yuan, 2002). Logging residues are usually located in remote regions, leading to difficulties for collecting and utilizing them. The amount of forest residues available used for renewable energy production is also affected by technical, ecological and environmental factors. In fact, the potential for renewable energy production from logging residues and wood-processing residues is estimated to be about 1286–1607 PJ and 228.5 PJ, respectively, accounting for 30–37.5% and 55% of logging residues and wood-processing residues in China (MOA, 2006).

In the future, climate policy is a key factor affecting the supply of residue biomass. Imposing carbon tax is projected to be an effective way to reduce CO_2 emissions and mitigate climate change (Wise *et al.*, 2009). Terrestrial carbon storage has been thought to be a low cost method to address the climate change. For example, soil carbon on croplands is a key component of terrestrial carbon storage. In China, croplands (over 130 M ha) contain 730 (329–1095) Tg C in the topsoil and are estimated to have sequestrated carbon at a rate of about 24.3 (11.0–36.5) Tg C yr^{-1} over the last 30 years (Yu *et al.*, 2012, 2013). Residue removal may lead to the loss of soil organic carbon, which can be minimized by improved management practices such as nitrogen fertilizer application, straw retention and incorporation and conservation tillage. These practices have been estimated to increase soil organic carbon from 38.5 Mg C ha^{-1} in 2010 to 56.9 Mg C ha^{-1} in 2050 on China's croplands (Yu *et al.*, 2013), which translate to \$2929 ha^{-1} in 2010 and \$18 711 ha^{-1} in 2050 with the carbon price under the CCS 450 ppm scenario. The carbon sequestration potential through optimal management is estimated to be approximately 2.39 Pg C over the next 40 years nationally (Smith *et al.*, 2007; Yu *et al.*, 2013). Nevertheless, the carbon sequestration potential in China after 2050 requires further evaluation under different future climate scenarios and management practices because soil carbon may reach a new equilibrium after 84 years of improved management practices and fertilizer amendment (Yan *et al.*, 2007; Yu *et al.*, 2013).

In this study, GCAM allows farmers to allocate the amount of residues to be retained on the field or to be removed for energy production, based on an economic assessment on carbon price, carbon stocks, the cost and benefit of the bioenergy (Wise *et al.*, 2009). Notably, imposing climate policies, such as carbon tax, can be difficult as it requires monitoring and evaluating terrestrial carbon emissions and stocks. Solutions to these barriers may require huge amounts of money to identify the landowners and transfer the decrease or increase of carbon stocks (Calvin *et al.*, 2014). One limitation of this study is that projected future utilization of residue biomass depends on a series of assumptions within GCAM including crop productivity, economic growth and land policy. Residue biomass production seems to be highly sensitive to future changes in crop productivity that may reduce land-use change emissions under the climate policy scenario (Wise *et al.*, 2009). In addition, the increasing demand for food to feed the rising world population may further limit residue availability (Gregg & Izaurralde, 2009; Gregg & Smith, 2010). As well, this will likely decrease unit mass collection cost and shift the supply curve accordingly. Dedicated energy crops will occupy more available agricultural land in order to achieve higher biomass yields while reducing production cost to compete with residue biomass by 2095. If crop yields increase only slightly or remain stable in the future, less residue biomass would be harvested because a higher proportion of the residue must be left in fields to maintain soil quality and reduce erosion. Management options that may increase residue removal rate include the practice of conservation tillage, better crop rotation and the introduction of catch crops. In addition, under a UCT regime, all carbon emissions to be taxed are simulated as the best policy to limit the CO_2 concentration. Forests with a higher below ground storage of carbon will be preferable due to their efficiency in limiting carbon emissions from land-use change. This implies that land polices limit the conversion from forests to bioenergy production and stress food production from agricultural lands (Calvin *et al.*, 2014).

In summary, China is the largest developing agricultural country in the world. Agricultural and forest residues in China have considerable potential to be available as a bioenergy source to provide ca. 10% of its total primary energy consumption in 2013. Accurate projection and successful utilization of residue biomass for energy production requires a comprehensive and multifactorial assessment. The integrated assessment results indicate that residue biomass for energy production could play an important role in mitigating the climate change. The production of bioenergy should be achieved in a sustainable way through optimal land management practices by conserving soil quality to enhance interactive economic, environmental and social purposes.

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